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CHAPTER 4

CABLE CHARACTERISTICS: ELECTRICAL

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1. VOLTAGE RATINGS OF CABLES

The rating, or voltage class, of a cable is based on the phase-to-phase voltage of the system even though the cable is single, two, or three phase. For example, a 15 kV rated cable (or a higher value) must be specified on a system that operates at 7,200 or 7,620 volts to ground on a grounded wye 12,500 or 13,200 volt system. This is based on the fact that the phase-to-phase voltage on a wye system is 1.732 (the square root of 3) times the phase-to-ground voltage. Another example is that a cable for operation at 14.4 kV to ground *must* be rated at 25 kV or higher since 14.4 times 1.732 is 24.94 kV.

The wye systems described above are usually protected by fuses or fast-acting relays. This is generally known as the 100 % voltage level and was previously known as a “grounded” circuit. Additional insulation thickness is required for systems that are not grounded, such as found in some delta systems, impedance or resistance grounded systems, or systems that have slow-acting isolation schemes. The following voltage levels are found in AEIC specifications [4-1 and 4-2].

1.1 100 Percent Level

Cables in this category may be applied where the system is provided with relay protection such that ground faults will be cleared as rapidly as possible, but in any case within 1 minute. While these cables are applicable to the great majority of cable installations that are on grounded systems, they may also be used on other systems for which the application of cables is acceptable provided the above clearing requirements are met in completely de-energizing the faulted section.

1.2 133 Percent Level

This insulation level corresponds to that formerly designated for “ungrounded” systems. Cables in this category may be applied in situations where the clearing time requirements of the 100 percent category cannot be met and yet there is adequate assurance that the faulted section will be de-energized in a time

not exceeding one hour. Also, they may be used when additional insulation strength over the 100 percent level category is desirable.

1.3 173 Percent Level

Cables in this category should be applied on systems where the time required to de-energize a section is indefinite. Their use is recommended also for resonant grounded systems. Consult the (cable) manufacturer for insulation thickness.

1.4 Cables Not Recommended

Cables are not recommended for use on systems where the ratio of the zero to positive phase reactance of the system at the point of cable application lies between -1 and -40 since excessively high voltages may be encountered in the case of ground faults.

1.5 Ratings of Low Voltage Cables

Low voltage cable ratings follow the same general rules as for the medium voltage cables previously discussed in that they are also based on phase-to-phase operation. The practical point here is that a cable that operates at say 480 volts from phase-to-ground on a grounded wye system requires an insulation thickness applicable to 480×1.732 or 831.38 volts phase-to-phase. This, of course, means that a 1,000 volt level of insulation thickness should be selected.

There are no categories for low voltage cables that address the 100, 133 and 173 percent levels. One of the main reasons for the thickness of insulation walls for these low voltage cables in the applicable Standards is that mechanical requirements of these cables dictate the insulation thickness. As a practical matter, all these cables are over-insulated for the actual voltages involved.

2. CABLE CALCULATION CONSTANTS

There are four main calculation constants that affect how a cable functions on an electric system: resistance, capacitance, inductance, and conductance. Conductor resistance has been addressed in Chapter 3.

2.1 Cable Insulation Resistance

The resistance to flow on a direct current through an insulating material

(dielectric) is known as insulation resistance. There are two possible paths for current to flow when measuring insulation resistance:

- (a) Through the body of the insulation (volume insulation resistance)
- (b) Over the surface of the insulation system (surface resistivity)

2.1.1 Volume Insulation Resistance. The volume insulation resistance of a cable is the direct current resistance offered by the insulation to an impressed dc voltage tending to produce a radial flow of leakage through that insulation material. This is expressed as a resistance value in megohms for 1000 feet of cable for a given conductor diameter and insulation thickness. Note that this is *for* 1000 feet, not *per* 1000 feet! This means that the longer the cable, the lower the resistance value that is read on a meter since there are more parallel paths for current to flow to ground. The basic formula for the insulation resistance of a single conductor cable of cylindrical geometry is:

$$IR = K \log_{10} D/d \quad (4.1)$$

where

- IR = Megohms for 1000 feet of cable
- K = Insulation resistance constant
- D = Diameter over the insulation (under the insulation shield)
- d = Diameter under the insulation (over the conductor shield)

Note: Both D and d must be expressed in the same units.

In order to measure the insulation resistance of a cable, the insulation must be either enclosed in a grounded metallic shield or immersed in water. Resistance measurements are greatly influenced by temperature—the higher the temperature, the lower the insulation resistance. The cable manufacturer should be contacted for the temperature correction factor for the specific insulation. Equation 4.1 is based on values at 60 °F.

The values shown in Table 4-1 are also based on this temperature. The ICEA minimum requirements of IR (sometimes referred to as “guaranteed values”) are shown as well to represent values that may be measured in the field. The actual value of IR that would be read in a laboratory environment are many times higher than these “minimum” values and approaches the “typical” values shown below.

Table 4-1
Insulation Resistance

Insulation	ICEA Minimum	Typical
HMWPE	50,000	1,000,000
XLPE & EPR, 600 V	10,000	100,000
XLPE & EPR, Med. V	20,000	200,000
PVC at 60 °C	2,000	20,000
PVC at 75 °C	500	5,000

2.1.2 Surface Resistivity. One of our contributors often states that “all cables have two ends.” These terminations or ends, when voltage is applied to the conductor, can have current flow over the surface of that material. This current adds to the current that flows through the volume of insulation which lowers the *apparent* volume insulation resistance unless measures are taken to eliminate that current flow while the measurements described above are being made. This same situation can occur when samples of insulation are measured in the laboratory. A “guard” circuit is used to eliminate the surface leakage currents from the volume resistivity measurement.

2.1.3 dc Charging Current. The current generated when a cable is energized from a dc source is somewhat complicated because there are several currents that combine to form the total leakage current. These currents are:

$$\begin{aligned} I_L &= \text{Leakage current} \\ I_G &= \text{Charging current} \\ I_A &= \text{Absorption current} \end{aligned}$$

The dc charging current behaves differently than the ac in that the dc value rises dramatically during the initial inrush. It decreases rather quickly with time, however. The magnitude of the charging and absorption currents is not usually very important except that it may distort the true leakage current reading. The longer the length and the larger the cable size, the greater the inrush current and the longer it will take for the current to recede. This initial current decays exponentially to zero in accordance with the following equation:

$$I_G = (E/R) e^{-t/RC} \quad (4.2)$$

where

$$\begin{aligned} I_G &= \text{Charging current in microamperes per 1000 feet} \\ E &= \text{Voltage from conductor to ground in volts} \\ R &= \text{dc resistance of cable in megohms for 1000 feet} \\ e &= \text{Base of natural logarithm (2.718281...)} \end{aligned}$$

t = Time in seconds

C = Capacitance of circuit in microfarads per 1000 feet

The absorption current is caused by the polarization and accumulation of electric charges that accumulate in a dielectric under applied voltage stress. The absorption current normally is relatively small and decreases with time. Absorption current represents the stored energy in the dielectric. Short-term grounding of the conductor may not give a sufficient amount of time for that energy to flow to ground. Removing the ground too quickly can result in the charge reappearing as a voltage on the conductor. The general rule is that the ground should be left on for one to four times the time period that the dc source was applied to the cable. The absorption current is:

$$I_A = A V C t^B \quad (4.3)$$

where

I_A	=	Absorption current in microamperes per 1000 feet
V	=	Incremental voltage change in volts
C	=	Capacitance in microfarads per 1000 feet
t	=	Time in seconds

A and B are constants depending on the insulation.

A and B are constants that differ with the specific cable since they are dependent on the type and condition of the insulation. They generally vary in a range that limits the absorption current to a small value compared to the other dc currents. This current decays rather rapidly when a steady-state voltage level is reached.

The current that is of the most importance is the leakage or conduction current. The leakage current is dependent on the applied voltage, the insulation resistance of the cable insulation, and any other series resistance in the circuit. This value becomes very difficult to read accurately at high voltages because of the possibility of end leakage currents as well as the transient currents. The formula for leakage current is:

$$I_L = E / R_I \quad (4.4)$$

where

I_L	=	Leakage current in microamperes per 1000 feet
E	=	Voltage between conductor and ground in volts
R_I	=	Insulation resistance in megohms for 1000 feet

The total current is:

$$I_T = I_G + I_A + I_L \quad (4.5)$$

The voltage must be raised slowly and gradually because of the rapid rise of I_G and I_A with time. Also, since both of these values are a function of cable length, the longer the cable length, the slower the rise of voltage is allowable. Equation (7-11) demonstrates the reason for taking a reading of leakage current after a specified period of time so that the actual leakage current can be recorded.

2.2 Dielectric Constant

Dielectric constant, relative permittivity, and specific inductive capacitance all mean the same. They are the ratio of the absolute permittivity of a given dielectric material and the absolute permittivity of free space (vacuum). The symbol for permittivity is ϵ (epsilon). To put this another way, these terms refer to the ratio of the capacitance of a given thickness of insulation to the capacitance of the same capacitor insulated with vacuum. (This is occasionally referred to as air rather than vacuum, but the dielectric constant of air is 1.0006). Since the calculations are usually not taken out to more than two decimal points, it is practical to use air for the comparison. The value of permittivity, dielectric constant, and SIC are expressed simply as a number since the dielectric constant of a vacuum is taken as 1.0000.

2.3 Cable Capacitance

The property of a cable system that permits the conductor to maintain a potential across the insulation is known as capacitance. Its value is dependent on the permittivity (dielectric constant) of the insulation and the diameters of the conductor and the insulation. A cable is a distributed capacitor. Capacitance is important in cable applications since charging current is proportional to the capacitance as well as to the system voltage and frequency. Since the charging current is also proportional to length, the required current will increase with cable length.

The capacitance of a single conductor cable having an overall grounded shield or immersed in water to provide a ground plane may be calculated from the following formula:

$$C = \frac{0.00736 \epsilon}{\log_{10} D/d} \quad (4.6)$$

where C = Capacitance in microfarads per 1000 feet

- ϵ = Permittivity of the insulating material. The terms permittivity (ϵ , epsilon), dielectric constant (K), and specific inductive capacitance (SIC) are used interchangeably. The term permittivity is preferred. See Table 4-2.
- D = Diameter over the insulation (under the insulation shield)
- d = Diameter under the insulation (over the conductor shield)

Note: Both D and d must be expressed in the same units.

Table 4-2
Permittivity, Dielectric Constant, and SIC

Material	Range	Typical
Butyl Rubber	3.0–4.5	3.2
PVC	3.4–10	6.0
Varnished Cambric	4–6	4.5
Impregnated Paper	3.3–3.7	3.5
Rubber-GRS or Natural	2.7–7.0	3.5
HMWPE	2.1–2.6	2.2
XLPE or TR-XLPE	2.1–2.6	2.3
XLPE, filled	3.5–6.0	4.5
EPR	2.5–3.5	3.0
Silicone Rubber	2.9–6.0	4.0

In single conductor, low-voltage cables where there is no semiconducting layer over the conductor, a correction factor must be used to compensate for the irregularities of the stranded conductor surface as shown in Table 4-3.

$$C = \frac{0.00736 \epsilon}{\log_{10} D / kd} \quad (4.7)$$

Table 4-3
Correction Factors for Irregularities

Number of Strands	Factor k
1 (solid)	1.0
7	0.94
19	0.97
37	0.98
61 & 91	0.985

2.4 Capacitive Reactance

The capacitive reactance of a cable is inversely dependent on the capacitance of the cable and the frequency at which it operates.

$$X_C = \frac{1}{2 \pi f C} \quad (4.8)$$

where X_C = Ohms per foot
 f = Frequency in hertz
 C = Capacitance in picofarads per foot

2.5 Charging Current for Alternating Current Operation

For a single conductor cable, the current may be calculated from the formula:

$$I_C = 2 \pi f C E \times 10^{-3} \quad (4.9)$$

where I_C = Charging current in milliamperes per 1000 feet
 f = Frequency in hertz
 C = Capacitance in picofarads per foot
 E = Voltage from conductor to neutral in kilovolts

Other leakage currents are also present, but the capacitive current has the largest magnitude. In addition, the capacitive charging current flows as long as the system is energized. The resistive component of the charging current is also dependent on the same factors as the capacitive current and is given by the formula:

$$I_R = 2 \pi f C E \tan \delta \quad (4.10)$$

where I_R = Resistive component of the charging current
 $\tan \delta$ = Dissipation factor of the insulation

The $\tan \delta$ of medium voltage insulation, such as crosslinked polyethylene and ethylene propylene, has values that are generally below 0.02 so the resistive component of the charging current is only a small fraction of the total charging current. The $\tan \delta$ is sometimes referred to as the insulation power factor since at the small angles these values are approximately equal. Since the capacitive charging current is 90° out of phase with the resistive charging current, the total charging current is generally given as the capacitive component and leads any resistive current flowing in the circuit by 90°. The result of these ac currents generated put demands on power required for test equipment.

2.6 Cable Inductive Reactance

The inductive reactance of an electrical circuit is based on Faraday's law. That law states that the induced voltage appearing in a circuit is proportional to the rate of change of the magnetic flux that links it. The inductance of an electrical circuit consisting of parallel conductors, such as a single-phase concentric neutral cable may be calculated from the following equation:

$$X_L = 2 \pi f (0.1404 \log_{10} S/r + 0.153) \times 10^{-3} \quad (4.11)$$

where

X_L = Ohms per 1000 feet

S = Distance from the center of the cable conductor to the center of the neutral

r = Radius of the center conductor

S and r must be expressed in the same unit, such as inches.

The inductance of a multi-conductor cable mainly depends on the thickness of the insulation over the conductor.

2.6.1 Cable Inductive Reactance at Higher Frequencies. Since the inductive reactance of an insulated conductor is directly proportional to frequency, the inductive reactance is substantially increased in higher frequency applications. Conductors must be kept as close together as possible. Due to the severe increase in inductive reactance at high frequency, many applications will require using two conductors per phase to reduce the inductive reactance to approximately one-half that of using one conductor per phase. A six conductor installation should have the same phase conductors 180° apart.

2.7 Mutual Inductance in Cables

In single-conductor shielded or metallic-sheathed cables, current in the conductor will cause a voltage to be produced in the shield or sheath. If the shield or sheath forms part of a closed circuit, a current will flow. (Shield and sheath losses are described under Ampacity in Chapter 12).

The approximate mutual inductance between shields or sheaths is given by the following relation:

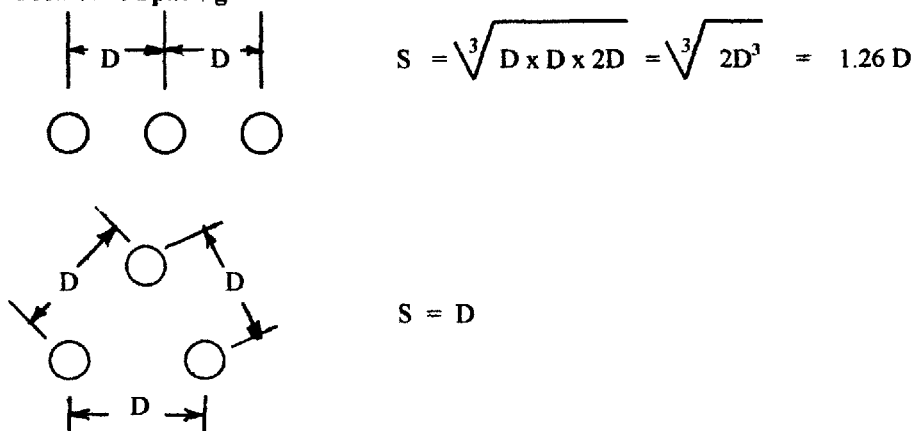
$$L_m = 0.1404 \log_{10} S/r_m \times 10^{-3} \quad (4.12)$$

where L_m = Henries to neutral per 1000 feet

S = Geometric mean spacing between cable centerlines in inches

r_m = Mean shield or sheath radius in inches. See Fig. 4-1.

Figure 4-1
Geometric Spacing



2.8 Cable Conductor Impedance

Conductor impedance of a cable may be calculated from the following equation:

$$Z = R_{ac} + jX_L \quad (4.13)$$

where

- Z = Conductor impedance in ohms per 1000 feet
- R_{ac} = ac resistance in ohms per 1000 feet
- X_L = Conductor reactance in ohms per 1000 feet

Conductor impedance becomes an important factor when calculating voltage drop. Since the power factor angle of the load and impedance angle are usually different, the voltage drop calculation can be cumbersome. The following voltage drop equation can be used for a close approximation:

$$V_D = R_{ac} I \cos \theta + X_L I \sin \theta \quad (4.14)$$

where

- V_D = Voltage drop from phase to neutral in volts
- R_{ac} = ac resistance of the length of cable in ohms
- $\cos \theta$ = Power factor of the load
- X_L = Inductive reactance of the length of cable in ohms

2.9 Total Cable Reactance

The total cable reactance (X) is the vector sum of the capacitive reactance and the inductive reactance of the cable in ohms per foot.

$$X = X_C + X_L \quad (4.15)$$

2.10 Cable Dissipation Factor

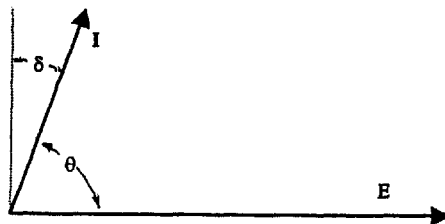
In cable engineering, the small amount of power consumed in the insulation (dielectric absorption) is due to losses. These losses are quite small in medium voltage cables, but can become more significant in systems operating above 25 kV. No insulating material is perfect.

In addition to the charging current flowing through the capacitive portion of the circuit, current also flows through the ac resistance portion of the circuit. This is the ac loss portion of the insulation circuit. The ratio of the ac resistance of the insulation to the capacitive reactance of the insulation is called the dissipation factor. This is equal to the tangent of the dissipation angle that is usually called $\tan \delta$. This $\tan \delta$ is approximately equal to the power factor of the insulation which is the $\cos \theta$ of the complementary angle.

In practical cable insulations and at 50 to 60 hertz, high insulation resistance and a comparatively large amount of capacitive reactance is present. There is virtually no inductive reactance. Hence the current leads the voltage by almost 90° . Since the cosine of 90° is zero, the cosine of an angle approaching 90° is small and the dissipation factor (often referred to as power factor of the insulation) also is small. Typical values for insulation power factor are 0.005 to 0.02 or slightly higher for other materials.

Dissipation factor is used in cable engineering to determine the dielectric loss in the insulation, expressed as watts per foot of cable that is dissipated as heat. It is also used to some extent to describe the efficiency or perfection of the insulation as a dielectric. Hence the term δ (delta) was chosen to represent the defect angle of the material.

Figure 4-2
Cable Insulation Power Factor or Dissipation Factor



2.11 Insulation Parameters

2.11.1 Voltage Stress in Cables. Voltage stresses in shielded cable insulations with smooth, round conductors is defined as the electrical stress or voltage to which a unit thickness of insulation is subjected. The average stress in volts per mil is determined by dividing the voltage across the insulation by the insulation thickness in mils.

$$S_{avg} = 2V / (D - d) \quad (4.16)$$

where

S_{avg}	= Average stress in volts per mil
V	= Voltage across the insulation
D	= Outer diameter of the insulation in mils
d	= Inside diameter of the insulation in mils

The stress is not uniform throughout the wall. The stress at any point in insulation wall can be calculated by the formula:

$$S = V / 2.303 r \log_{10} (D/d) \quad (4.17)$$

where

S	= Stress in volts per mil at a point in the insulation r mils from the cylindrical axis.
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The maximum stress occurs at the surface of the conductor shield.

$$S_{max} = 0.868 V / d \log_{10} (D/d) \quad (4.18)$$

where

	The units are the same as in (4.15, 4.16 and 4.17).
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2.11.2 Dielectric Strength. Although maximum and average stress are important, dielectric strength is usually specified as the average stress at electrical breakdown. The dielectric strength of a material depends on the dimensions and the testing conditions, particularly the time duration of the test. A thin wall of material generally withstands a higher average stress before breaking down than a thicker wall.

2.11.2.1 ac Dielectric Strength. These measurements are made in two ways:

Quick-rise or
Step-rise.

In the quick-rise method, the voltage applied to the insulation is raised at a uni-

form rate until the insulation breaks down. As an example, a rate of rise of 500 volts per second is known as "quick-rise."

In the "step-rise" method, the voltage is raised to a predetermined level and held at that level for an amount of time, such as five or ten minutes at each level, until breakdown occurs. A relatively short time, say the five or ten minutes described above, has the advantage of reaching breakdown in a shorter amount of total test time. In the real world, the time at a voltage level is much longer, so some cable engineers prefer a longer step time such as 30 minutes or one hour at each step. With the longer step times, the breakdown voltage is lower than with the quick-rise or short step time methods.

2.11.2.2 Impulse Strength. Because cable insulation is frequently subjected to lightning or switching surges, it is often desirable to know the impulse strength of the cable. Surges of "standard" wave shape, such as eight seconds to reach 90% of crest value, and 40 microseconds to drop to one-half of crest value, are frequently used in the laboratory. The increasing voltages are applied to the insulation with several surges at a negative potential and then, at the same voltage level, the same number of surges are applied with positive pulses. The average stress in volts per mil is calculated from the crest voltage of the surge on which breakdown occurs.

3. REVIEW OF ELECTRICAL ENGINEERING TERMS

These terms apply to all electrical engineering circuits. The actual application of these terms to cables is covered in section 2.0 of this chapter.

3.1 Resistance

(R) is the scalar property of an electric circuit which determines, for a given current, the rate at which electric energy is converted into heat or radiant energy. Its value is such that the product of the resistance and the square of the current gives the rate of conversion of energy.

In a direct-current circuit,

$$R = E/I \quad (4.19)$$

and $P = I^2 R \quad (4.20)$

where $R =$ Resistance in ohms
 $E =$ Electromotive force in volts

I = Current in amperes

P = Power in watts

3.2 Conductance

(G) is the property of an electric circuit which determines, for a given electromotive force in the circuit or for a given potential difference between the terminals of a part of a circuit, the rate at which energy is converted into heat or radiant energy. This value is such that the product of the conductance and the square of the electromotive force, or potential difference, gives the rate of conversion of energy.

$$P = E^2 G \quad (4.21)$$

where

P = Power in watts

E = Voltage, phase to ground, in kilovolts

G = Conductance in mhos

The unit of conductance is the mho. Conductance is the reciprocal of resistance.

$$G = 1 / R \quad (4.22)$$

where

G = Conductance in mhos

R = Resistance in ohms

3.3 Volume Resistivity

Volume resistivity of a material is the reciprocal of conductivity. The unit for volume resistivity is ρ (rho). It is the resistance of a section of material of unit length and unit cross-section.

$$R = \rho l / a \quad (4.23)$$

where

R = Resistance

ρ = rho, volume resistivity

a = Area

l = Length

3.4 Conductivity

Conductivity of a material is the direct-current conductance between the opposite, parallel faces of a portion of the material having unit length and unit

cross-section. The unit for this is γ (gamma). It is the reciprocal of resistivity.

$$G = \gamma a / l \quad (4.24)$$

where G = Conductance
 a = Area
 l = Length

3.5 Inductance

Unit L represents the scalar property of an electric circuit, or two neighboring circuits, which determines the electromotive force induced in one of the circuits by a change of current in either of them.

3.5.1. Self Inductance. This is the property of an electric circuit that determines, for a given rate of change of current in the circuit, the electromotive force induced in the same circuit.

The unit of inductance is one henry. One henry is the self inductance of a closed circuit in which an electromotive force of one volt is produced when the electric current transversing the circuit varies uniformly at the rate of one ampere per second.

$$e_l = -L \, di_l / dt \quad (4.25)$$

where e_l and i_l are in the same circuit and L is the coefficient of self inductance.

3.5.2. Mutual Inductance. (L_m) is the common property of two associated electric circuits that determines, for a given rate of change of current in one of the circuits, the electromotive force induced in the other.

3.6 Capacitance

This is the property of an electric system comprising insulated conductors and associated dielectric materials which determines, for a given time rate of change of potential difference between the conductors, the displacement currents in the system.

3.7 Reactance

Reactance is the product of the sine of the angular phase difference between the current and potential difference times the ratio of the effective potential differ-

ence to the effective current, there being no source of power in the portion of the circuit under consideration. The total reactance of a circuit is the sum of the inductive and capacitive reactance.

3.8 Impedance

Impedance is the ratio of the effective value of the potential difference between the terminals to the effective value of the current, there being no source of power in the portion of the circuit under consideration.

3.9 Admittance

(Y) is the reciprocal of impedance.

3.10 Power Factor

(F_p) is the ratio of active power to apparent power. Apparent power (S) consists of two components; active (in-phase) power P_a , which does useful work and reactive (out-of-phase) power P_r .

4. REFERENCES

[4-1] Association of Edison Illuminating Companies, *Specifications for Thermoplastic and Cross-Linked Polyethylene Insulated Shielded Power Cables Rated 5 Through 46 kV*, Specification CS5-94, 10th Ed., New York, NY, AEIC, 1994.

[4-2] Association of Edison Illuminating Companies, *Specifications for Ethylene Propylene Insulated Shielded Power Cables Rated 5 Through 69 kV*, Specification CS6-96, 6th Ed. New York, NY, AEIC, 1996.